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ABSTRACT

Chaos theory is being used as a tool to study a wide variety of phenomena. It is a philosophical and empirical approach that attempts to explain relationships previously thought to be totally random. Although some relationships are truly random, many data appear to be random but reveal repeatable patterns of behavior under further investigation. Chaos theory is concerned with chaotic systems that demonstrate: (1) constrained randomness; (2) self-referential systems (feedback mechanisms); and (3) fractals (dimensions that are a measure of the relative degree of complexity of an object). Another fundamental characteristic of chaotic systems is sensitivity to initial conditions. Many parallels exist between chaos theory and traditional research methodologies, as illustrated via a discussion of the concept of strange attractor (the phase space diagrams of chaotic systems), and much controversy surrounds applications of chaos theory. Because chaos theory is essentially systems oriented, it has many possible applications in education. The most immediate will come from study of individual brain function and how people learn. A new frontier in chaos theory is its application to organizational structures, which may give valuable insights into classroom structure and building and district organizations. Accuracy of communications, centralization versus decentralization, and control of disruptive behaviors in the classroom are a few examples of likely candidates for this type of research. Sixteen figures are included. (SLD)

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CHAOS MODELING: INCREASING EDUCATIONAL RESEARCHERS' AWARENESS OF A NEW TOOL

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CHAOS MODELING: INCREASING EDUCATIONAL RESEARCHERS' AWARENESS OF A NEW TOOL

Chaos theory is being used as a tool to study a wide variety of phenomenon. In recent years, subjects as diverse as quantum mechanics (Pool, 1989D), astronomy (Pool, 1989F), population dynamics (Pool, 1989B), turbulent flows (Gleick, 1987), brain disease (Babloyantz & Destexhe, 1986), economics (Pool, 1989F), cardiology (Pool, 1989C), immuniology (Gleick, 1987), epidemiology (Pool, 1989A), weather (Pool, 1989E), and geology (Gleick, 1987) have been analyzed in this context. The results have been startling, exciting, and challanging. Not only are these applications of the theory providing the scientific community with new information, they are also providing the grist for a reanalysis of what it means to "do science." The basic tenets of the positivistic reductionist approach to scientific inquiry so prevalent in Western Society are being challenged.

The purpose of this paper is to explain chaos theory, to relate it to traditional research methodologies, and to focus attention on several areas of chaos research which may be of importance in educational settings. The philosophical implications of chaos theory will be discussed, especially as they relate to quantitative and qualitative methodologies.

It should be noted from the outset that the actual

application of chaos theory involves a fair amount of sophisticated mathematics (Schuster, 1988) and involvement by someone who is reasonably comfortable working in the area of nonlinear dynamics. The math, however, is only a tool to an end. It does not require an intimate knowledge of advanced mathematics to understand chaos, what it explains, or why it is creating so much excitement in the scientific community.

Chaos Theory Explained

The first part of this paper attempts to explain chaos theory in a way that is useful to educational reaseachers. It is divided into four sections: the concept of chaos; the tenets of chaos; the concept of chaos revisited; and organizing chaos research.

The Concept of Chaos. Chaos theory is a philosophical and empirical approach that attempts to explain relationships that were previously thought to be totally random. Some relationships are truly random. However, in some instances, data previously thought to be random exhibits reappearing patterns. The presence of these patterns suggests that the data are not truly random.

Chaos, in the context of chaos theory, can be defined as

nonrandom behavior that cannot be accurately predicted on a long-term basis. Chaotic systems are those systems which display the chaotic behavior defined above. Their behavior appears to be random, but further investigation reveals repeatable patterns of behavior. Though researchers have various methods for representing these patterns, they cannot be used to accurately predict the behavior of the system.

The Tenets of Chaos. One way to demonstrate the existence of these patterns is to play the chaos game (Nova, 1989). Suppose that three points are placed on a piece of paper in a pattern that forms an equilateral triangle. The first point is labled 1 and 2, the second, 3 and 4 and the third, 5 and 6. Now suppose that a point is chosen randomly. This will serve as the starting point.

The game is played by rolling a die, moving halfway from the current position to the point whose number came up, and placing a new point at this position on the paper. Since each roll of the die is a random event, it is logical to assume that the distribution of points that are placed on the paper is also random. However, if the game is played long enough, a triangle within triangle pattern emerges.

Slide # 1

A very orderly pattern arises as a result of a random process!

This example can be used to illustrate a number of concepts associated with chaotic systems. Among these are constrained randomness, self-referential systems (feedback mechanisms), and fractals.

Constrained randomness can easily be seen in the slide. The process that produced this pattern was a series of random rolls of the die. Yet the pattern is not random. It has definite boundaries. This feature of randomness within constraints is a characteristic of chaotic processes as distinct from true randomness.

Self-referential systems can also be seen in the slide. The pattern repeats itself on an ever decreasing scale. This pattern is representative of the random process that created it. Each successive point was halfway from the previous point to the triangle corner represented by the random role of the die. That is, each new point was dependent on the position of the point that came before it. The presence of such a feedback loop is another characteristic of chaotic processes.

Fractals are also represented in the slide. In one sense, this concept was already introduced when the ever decreasing scale of the pattern was discussed as an example of a self referential system. As a matter of fact, the pattern is repeated

in exact detail, no matter how small a scale is investigated. Some graphic representations of fractals are extremely complex and at the same time extremely beautiful. One such example is the Mandelbrot Set.

Slide # 2 - 5

This fractal image happens to be created using an iterative process on complex numbers. Nature, however has an ample supply of fractals not the least of which are such ordinary items as snow flakes and coast lines.

Fractals can easily be created. Imagine an equilateral triangle. On each side of the triangle draw another equilateral triangle one third the size of the original and center it on the middle third of each side. Continue this process indefinitely. This figure is known as the "Koch Island" and was introduced to mathematicians by Helge von Koch in 1904 (Peterson, 1988).

Slide # 6

It is not hard to imagine that the perimeter of the figure increases to infinity. This is a curious fact since the triangle never takes up much more of the plane than a circle circumscribed

around it.

Fractals however represent more than patterns within patterns. They represent a "world" of **partial dimensions.** Euclidian geometry is a geometry of three dimensions. It is the geometry of everyday life. It holds that a point has no dimension, a line has one, a plane two and a solid has three dimensions. Fractal geometry is different. It is a geometry of partial dimensions. Most everyday examples, however, are in the zero to three plus range. The coastline of Great Britain, for example, has a fractal dimension of 1.26 (Briggs & Peat, 1989).

One way of visualizing a dimension between one (line) and two (plane) is to create a Peano curve. This curve was discovered by Giuseppe Peano in 1890 (Briggs & Peat, 1989).

Slide # 7

The curve is created by starting out with a straight line which is successively folded. It can be shown that the line can touch every point in the plane without ever crossing itself. In the beginning, the line is straight and truly represents one dimension. At the point where the line touches every point in the plane, the plane (made up of a one dimensional line) truly represents two dimensions. Since, as the line is successively

folded, it touches a higher and higher percentage of the points that make up the plane, it is logical to think of the figure as having a dimension greater than one but less than two in these intermediate stages.

One last point needs to be made about fractals. Dimensionality is relative. Imagine looking at a ball of yarn from far away. It looks like a point (zero dimensions). At some closer range, the ball appears to be a three dimensional sphere. Closer still and all that may be viewed is a single strand that appears as a one dimensional line which upon closer inspection again takes on three dimensions. Beniot Mandelbrot, creator of fractal geometry, refers to the **effective fractal dimension** of an object. Implied in this concept are the ideas that quantity is a relative -- it always involves smearing out some of the details, and that fractal dimensions are a measure of the relative degree of complexity of an object. Mandelbrot thinks of the measure of "effective fractal dimension" as a qualitative measure.

The presence of fractal dimensions is characteristic of chaotic processes. The detection of fractals in nature is an indication that a chaotic process may be involved.

Constrained randomness, self-reference (feedback mechanisms), and fractals are properties of chaotic systems that could be shown graphically. Another type of graph, a phase space diagram, has also been used to depict chaos. Attractors, limit

cycles, point attractors, and strange attractors represent particular patterns in phase space which are often discussed in connection with chaos theory. These concepts are presented below.

Phase space diagrams, show the complete history of a system across time. A single point is used to represent the state of the system at any given time. The trajectory of the point over time represents the history of the system. For purposes of illustration, imagine the regular movement of the pendulum of a grandfather clock. Its motion is very regular and can be completely described using two variables, position and momentum. This information can be plotted on an X-Y coordinate system.

Slide # 8

The path of the point in phase space that represents the motion of the pendulum would be an oval. Each successive cycle retraces the same path. In phase space terminology, this path is called an **attractor** since it represents the ultimate motion of the system. In this particular type of system, where the trajectory is an oval, the trajectory is also refered to as a **limit cycle.**

A simple pendulum, one that is not part of a clock, can be

used to illustrate another kind of attractor, a **point attractor.** This time the pendulum settles down and ends motionless. The phase space diagram looks like a spiral with the ultimate state, the point attractor in the middle.

Slide # 9

While the applications of phase space described above used examples from physics requiring only two dimensions and represented nonchaotic systems, this does not have to be the case. It is possible to represent ecosystems such as trout, pike, and anglers or virtually any other system. In order to do this, the number of dimensions of phase space increases in direct proportion to the number of variables necessary to completely describe the system at any point in time. In fact, complex chaotic systems with their constrained randomness, feedback loops and fractal dimensions can be completely represented in phase space.

Strange attractor is the term used to describe the phase space diagrams of chaotic systems. One of the earliest was based on work done by Edward Lorenz in the early 1960's. The focus of Lorenz's research was weather prediction. Most of the work at that time took the form of prediction equations. Efforts focused on locating the right combination of variables and obtaining

accurate measures of those variables. Lorenz took a different approach. He programmed into his computer a system of nonlinear differential equations that he thought completely described atmospheric conditions, provided starting values, and watched as the computer calculated future weather patterns.

Slide # 10

The phase space diagram produced from these calculations was something very different from the regular attractors found in nonchaotic systems. Here was the constrained randomness of chaos. Within the boundries of the system, the trajectory was truly random. Today, this strange attractor is known as the Lorenz Attractor.

There is more than just qualitative information available in a phase space diagram. A measure of how much space the figure takes up and how complex the figure is can also be derived. This measure is referred to as the **dimension** of the plot with higher values associated with more complex systems. The measure calculated is the fractal dimension discussed earlier. Experimental data from a variety of disciplines has indicated that real world systems very often exhibit noninteger dimensionality.

Sensitivity to Initial Conditions is another fundamental characteristic of chaotic systems. Lorenz's work with weather prediction was responsible for focusing attention on this phenomonon. Lorenz found that the initial values of variables used as the starting point in computer runs greatly affected the results. This came about quite by accident. One day he restarted a projection with values taken from a previous run and was amazed to find that the new projection predicted weather patterns that increasing diverged from the original predictions over time. At first he thought the computer had malfunctioned. Only later he realized that he had started the second run with variable values from his printout which were to three decimal places while the computer had used values to six decimal places during the original run.

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These findings lead Lorenz to a startling conclusion. Long range weather forecasts are not possible, because initial conditions can never be known with enough accuracy. Today this phenomenon is known as the **butterfly effect.** It implies that a butterfly flapping wings in Beijing will introduce enough uncertainty into the values that the model will diverge from reality in a very short period of time.

Routes to Chaos provide a basis for practical applications of chaos theory as well as a greater understanding of sensitivity to initial conditions.

Order does not instantanously turn to randomness. Something happens at the boarder and that something is process that involves **bifurcations**. It involves the concept of sensitivity to initial conditions and the idea that some initial values of variables in a chaotic system lead to predictable results while others lead to random results. A system or set of equations which meet these conditions is said to be **nonlinear**.

A nonlinear chaotic system described by P. F. Verhulst in 1845 can be used to illustrate these ideas. He was interested in describing the growth of an animal population in a closed system. In order to predict the population growth mathematically, he created what appeared to be a simple algebraic equation. Today, the equation is known to represent a chaotic system of infinite complexity (Peterson, 1988).

Slide # 12

In this equation, the "X sub n" represents the current year population, the "B" represents a variety of environmental parameters such as available food, shelter, etc. which

ultimately affect the birth rate, and the "X sub n+1" represents the next years population. The terms "X sub n" and "(1 - X sub n)" oppose one another. In practical terms, if "X" gets too large, "(1 - X sub n)" has the effect of decreasing the survival rate and thus keeps the population within the carrying capacity of the environment.

It should be noted that simple inspection of the equation shows that it contains one of the characteristics of chaotic systems- it is self-referential. Information from the previous generation is used to predict the next generation for each iteration of the equation.

One would expect that this simple appearing equation would behave in a simple linear manner. For many inital values of the "B" parameter this is true. But at some point strange things begin to happen.

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At a certain initial value of "B" the equation predicts two values of the next generation. At certain higher value, each of these split again producing four possible outcomes of the population. This splitting or bifurcation occurs again and again and is referred to as **period doubling**. At some point, there are

so many possible outcomes that the system is said to be chaotic.

Another important point to be made about chaotic systems that have entered a state of chaos is that chaos is not a totally random process.

Slide # 14

Certain initial values of the "B" parameter will lead to reasonable predictable outcomes. For instance, a value 3.83 will lead to only three possible population values. The population will jump back and forth between these values. There are areas of reasonable predictability spread throughout the chaotic region. Even within regions that are very chaotic, not all possible population values are equally likely.

Given the conditions described above, it is easy to understand the concept of sensivity to initial conditions. A wide range of initial conditions lead to stable state. But at some point, the system moves toward chaos over a relatively narrow range of initial parameter values. Once in chaos, even a small change in initial conditions can lead to drastically different results.

Earlier the Lorenz Attractor was described as the result of the chaos inherent in the equations Lorenz used to describe his

weather model. It was said to represent confined randomness.

Slide # 15

This attractor is the end result of predicting months into the future. Initially the phase space diagram contains only one trace. Over time, the trajectory splits in two (first bifurcation: two cycle). Later still, each trajectory bifurcates again (second bifurcation; four cycle) and so on into chaos.

One last and very important point should be made about the period doubling process. In the summer of 1975, Mitchell Feigenbaum discovered a universal scale to the period-doubling transformations of chaotic systems as diverse electrical circuitry, optical systems, business cycles, and populations. In effect he discovered a way to predict when period doubling would occur in chaotic systems. His discovery has become known as the **Feigenbaum Number** (Gleick, 1987).

The Concept of Chaos Revisited. Chaos theory provides a method for describing nonlinear systems which are self-referential. It is a characteristic of systems in which there is a delicate balance between forces of stability and forces of instability (Gleick, 1989). One of the reasons chaos theory is so exciting has to do with the way the world seems to

be "put together." A vast number of phenomenon found in the world fit this description. Yet most have gone virtually unstudied. Traditional science had no methods for working with these types of systems. It is now possible to begin to explore a whole range of new phenomenon and to revisit issues that were previously intractable.

Organizing Chaos Research. In exploring already existing applications of chaos theory, it may be helpful to classify phenomenon as normally chaotic or normally orderly. Very often, the practical applications that arise from research relate to finding ways of stopping a system from crossing the border from the side which represents the system's normal state to the opposite condition.

Nonlinear systems that normally function in a nonchaotic fashion are common in the everyday environment. Two examples include the beating of a human heart and computer networks. When these systems cross the border to chaos, the results are fibrillation and incorrect answers, respectively (Briggs, 1989). Most persons have had at least indirect contact with heart disease, but knowledge of chaotic computers is less common. Two examples, both involving computer networks, are a TRW network operating in Europe and a network of parallel processors created by XEROX (Briggs & Peat, 1989).

Nonlinear systems that normally function in a chaotic

fashion are not as obvious. An excellent example of one such system is the human brain. The normal state of affairs for the mind is chaos. Walter Freeman (U.C.L.A., Berkley) believes that mental activity alters this chaotic background (Pool, 1989C). Paul Rapp (1985) has measured the dimensionality of phase space diagrams constructed from EEG data of subjects resting with their eyes closed and found them to be approximately 2.3. The introduction of a mental task, counting backwards from 700 by sevens, caused the dimensionality to increase to 2.9. Agnes Babloyantz and A. Destexhe (1986) using similar procedures calculated the dimensionality of the EEG patterns of persons undergoing epileptic seizures and found it to be in the order of 2.0. The interpretation of this data has been to suggest that a loss (even a partial loss) of chaos can lead to pathology.

Methodology and Paradigms

Quantitative research involves assigning numbers to objects and using this data in a predictive sense. It is a philosophy of research that assumes that the environment is predictable if enough information is available. Emphasis is placed on reliability and validity. Qualitative research, on the other hand, postulates that the vary act of measuring an object changes

it. Successive measures of the same object may produce different answers. Every situation is unique and emphasis is placed on describing a situation for its own sake. While the definitions presented above are oversimplifications, they serve to illustrate the point that qualitative and quantitative methodologies have sometimes been viewed as mutually exclusive (Cook & Reichardt, 1979). More recent discussions have suggested that this is a false dichotomy, that these methods are part of an interactive continuum (Newman & Benz, 1985).

How one deals with the "constrained randomness" of chaos depends on one´s philosophical perspective. A quantitative reseacher would say that the behavior is not truly random. He/she would strive to adequately quantify all of the system´s variables so that accurate prediction is possible. The quantitative researcher works to explain and therefore eliminate randomness. A qualitative researcher, however, would consider the "randomness" of the system as part of the data, a manifestation of the system that should be worked into theory rather than eliminated.

Seemingly random behavior in a system can be looked at another way. This randomness could be considered analogous to the concept of outliers in so-called linear systems. Depending on one´s point of view, the outlier is treated differently. From a quantitative perspective, the outlier is considered an anomaly

and is thrown out of the statistical analysis. From a qualitative perspective, the outlier is considered a meaningful part of the data and is retained in whatever methodologies are applied.

Chaos theory affirms this latter approach in its methodologies. One of the major characteristics of qualitative research is that it looks at the data and derives its theory from the data. Interpretation, explanation, and insight emerge from the data. Chaos researchers follow this same methodology. They study a system in order to see what emerges from it. Quite often, previously held theories about the system fail to accurately predict its behavior. A more concrete example of chaos modeling as a qualitative method is the strange attractor.

The process that produces the attractor involves the plotting of a great many data points which represent the behavior of the system. This pattern is not apparent when only a few points are plotted. It depends on the inclusion of all the states that the system assumes over time. Likewise, an underlying pattern of behavior in a "human" system may not manifest itself because too few examples are being studied. Chaos theory would suggest that the outlier is also part of the system and is connected to it by some underlying principle.

Other parallels exist between chaos theory and traditional research methodologies. The strange attractor can be thought of

as representing an underlying construct or principle of a system and as such can be equated conceptually with a factor. Factor analysis is done to produce factors which are assumed to measure or represent underlying constructs in the behavior being studied. Factors are derived by running a series of correlations to determine the structure of the data. Based on the factor loadings, the researcher can interpret the structure by naming the construct which the data seems to represent. Likewise, a strange attractor is produced by plotting what can be considered a series of correlation points, or the relationships between variables at a given moment in time. The shape that results is one that can be replicated in further studies of the same system.

As the complexity of a system increases, so does the number of variables needed to describe its behavior. The attractor will have as many dimensions as there are variables in the system. The behavior of a simple system may be represented by two or three dimensions, while a more complicated system will require many more dimensions. Obviously, an attractor of four or more dimensions is hard to visualize. This is somewhat analogous to factor analysis of a complex system in that a complex system will produce more factors and is considered multidimensionally complex. When the researcher names the factors, he or she is interpeting the data. At this point in time it does not appear that this approach has been applied to strange attractors.

Chaos theory, however, does not fit conveniently on the continuum at just one point. It depends on how it is used. Some applications, such as the heart (Briggs & Peat, 1989) and brain (Rapp, 1985; Babloyanz & Destexhe, 1986) studies cited earlier are primarily descriptive. Other research, for example Goldberger and West's (1987) work on developing practical applications of chaos theory in the area of clinical cardiology focus on prediction.

It is important when reading various authors to realize that their presentation and discussion of chaos theory, whether using it in a descriptive or predictive sense, is influenced by their philosophical position. Being unaware of an author's position can produce a totally different interpretation of the information.

An example will serve to illustrate the problem. Briggs and Peat (1989) have echoed Lorenz's sentiments that long term (and in fact) near term prediction of chaotic systems is impossible because of sensitivity to initial conditions. How then can others "do chaos research" in a predictive sense? There appear to be two components to the answer. The first is that they change the question of interest and the second is that they capture information about the whole system and do not worry about the values of the starting parameters that lead to the current state of the system.

Changing the question of interest involves changing the focus from trying to predict the future of the system based on a particular value of the starting parameter to knowing how to manipulate the starting parameter in a way that will push the total behavior of the system in the desired direction.

This point can be demonstrated by referring to the logistic map used to show the possible outcomes of population growth in a closed system presented earlier.

Slide # 16

Assume a managed ecosystem such as a fish hatchery that has become chaotic. Fish production is no longer predictable. Some generations the population increases and for others it decreases. Since the "B" parameter represents the birth rate, manipulating the environment in a fashion that will decrease its value and bring it within the range of the steady state region will actually increase overall predictability.

The manipulation of the "B" parameter is the basis for many of the "predictive" applications of chaos theory. In some applied settings, there is an attempt to detect the onset of chaos and manipulate the system prior to the time chaos actually sets in. Goldberger and West's (1987) work in clinical

cardiology provides such an example. In other settings, there is an attempt to detect decreases in the amount of chaos as measured by decreases in the fractal dimension of a systems phase space pattern and to manipulate the system prior to the onset of pathology. Babloyantz and Destexhe´s (1896) work with epilepsy certainly has this potential.

The practical applications of chaos theory encapsulate the major differences in the philosophical orientation surrounding chaos. Some proponents view chaos theory as wholistic. They view chaos as dealing with the complete system, its sensitivity to initial conditions and all of its intricate feedback mechanisms at once. Chaos is viewed as legitimizing the detection of randomness as an appropriate scientific goal and as making long term prediction impossible. The implication is that the positivistic reductionist approach to science that has been the mainstay of Western Society will be overturned. Persons who espose this position include Jim Yorke of the University of Maryland who in the early 1970´s coined the word "chaos" and Joseph Ford of the University of Georgia (Pool, 1989F).

Others view chaos theory as another technique to better understand problems that were already known to exist. For example, Richard Brewer of IBM developed a method for causing barium atoms to move from stability to chaos and back to stability by varing the electromagnetic field in which they were

placed and Jack Wisdom of the Massachusetts Institute of Technology discovered that Hyperion, a moon of Saturn has a chaotic orbit. In each case, however, these systems behave according to well-accepted physical principles. What is different is that the equations which describe these systems lead to chaotic solutions for these particular examples (Pool, 1989F).

There is certainly much controversy surrounding chaos theory, be it discussions about quantitative versus qualitative, wholistic versus reductionistic, or of paradigm shifts versus simply better understanding what is already known. For the person who is considering applying chaos theory to his or her area of interest, it may be more functional to focus on the possible range of applications and to be aware of his or her own biases and the biases of the authors he/she is reviewing.

Chaos Research and Education

Since chaos theory is essentially systems-oriented, one way to organize potential applications in educational settings is by level of system. Using this approach, student-, classroom-, building-, and district-centered categories could serve as a framework for organizing the research.

Perhaps the most immediate applications of chaos research will come from knowledge gained by the study of individual brain function. The research previously referenced focused primarily on the nervous system's transition to abnormal conditions. However, there is considerable work underway which attempts to understand the brain as it functions under normal conditions.

Walter Freeman (UCLA) and Christine Skarda (Ecole Polytechnique in Paris) have studied phase diagrams of EEG activity from the olfactory bulbs of rabbits in order to understand learning and memory. They found that the normal, alert state of the brain was chaotic. After initial introduction to a particular odor, subsequent reintroduction would momentarily decrease the complexity of the chaos. Even more exciting is the fact that they were able to identify unique patterns for each type of odor. These patterns changed from rabbit to rabbit but remained consistent within rabbit (Skarda & Freeman, 1987). Freedman and Bob van Dijk subsequently reported similar results in EEG based phase diagrams from the visual cortex of monkeys (cited in Pool, 1989C).

Paul Rapp at the Medical College of Pennsylvania has focused on categorizing the fractal dimensions of the human brain while his subjects complete various mental tasks. He has found that mental activity increases the amount of chaos present (Rapp, 1987).

Arnold Mandell of the University of California believes that he might be closing in on a strange attractor which represents the "personality" of an individual. He believes that data from the firing rate of dopamine receptors, serotonin receptors, and single cells in EEG activity all evidence the same strange attractor for any given individual (cited in Briggs & Peat, 1989).

New maps of the brain, representative of the nonlinear feedback nature of chaos are being created. One example is the model developed by Matte Bergstrom of the University of Helsinki, Findland. He refers to his model as a "bipolar generator" and divides the brain into an information end and a random or chaos end. He believes it is the interaction of these ends that produce thought and behavior (cited in Briggs & Peat, 1989).

Much of the research in this area is not more than five to eight years old. As it progresses, it is highly probable that it will produce information about how people learn. While many educational researchers may not have the resources to carry out these types of studies, there is little doubt that an understanding of the physiology of learning has unlimited heuristic potential for education.

One of the newest frontiers of chaos theory is its application to organizational structures (Pool, 1989F). Methodologies are just now being developed. Classroom, building,

and district-wide studies are really studies of organizational behavior. These types of systems are often nonlinear and replete with feedback mechanisms- the very grist of chaos theory.

Today, systems theory generally subsumes these types of investigations. Systems theory has been acclaimed the wave of the future by persons such as Alvin Toffler, John Naisbitt, Hazel Henderson, and Marilyn Ferguson (Briggs & Peat, 1989).

One of the leading proponents of systems theory applications to organzational structure is Peter Senge of the Massachusetts Institute of Technology. He founded the Systems Dynamics Group and has taught dozens of municipalities and corporations how to deal with management problems through nonlinear "modeling" (cited in Briggs & Peat, 1989).

Application of the techniques and methodologies being developed by systems-oriented social scientists such as Senge may provide valuable insights into classroom structure and building and district organization. Accuracy of communications, centralization versus decentralization, and control of disruptive behaviors in the classroom are but a few examples which appear to be likely candidates for this type of research.

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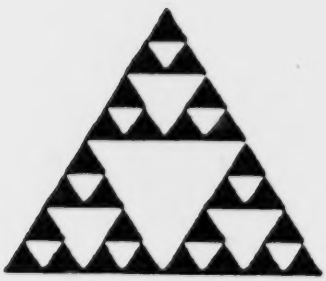
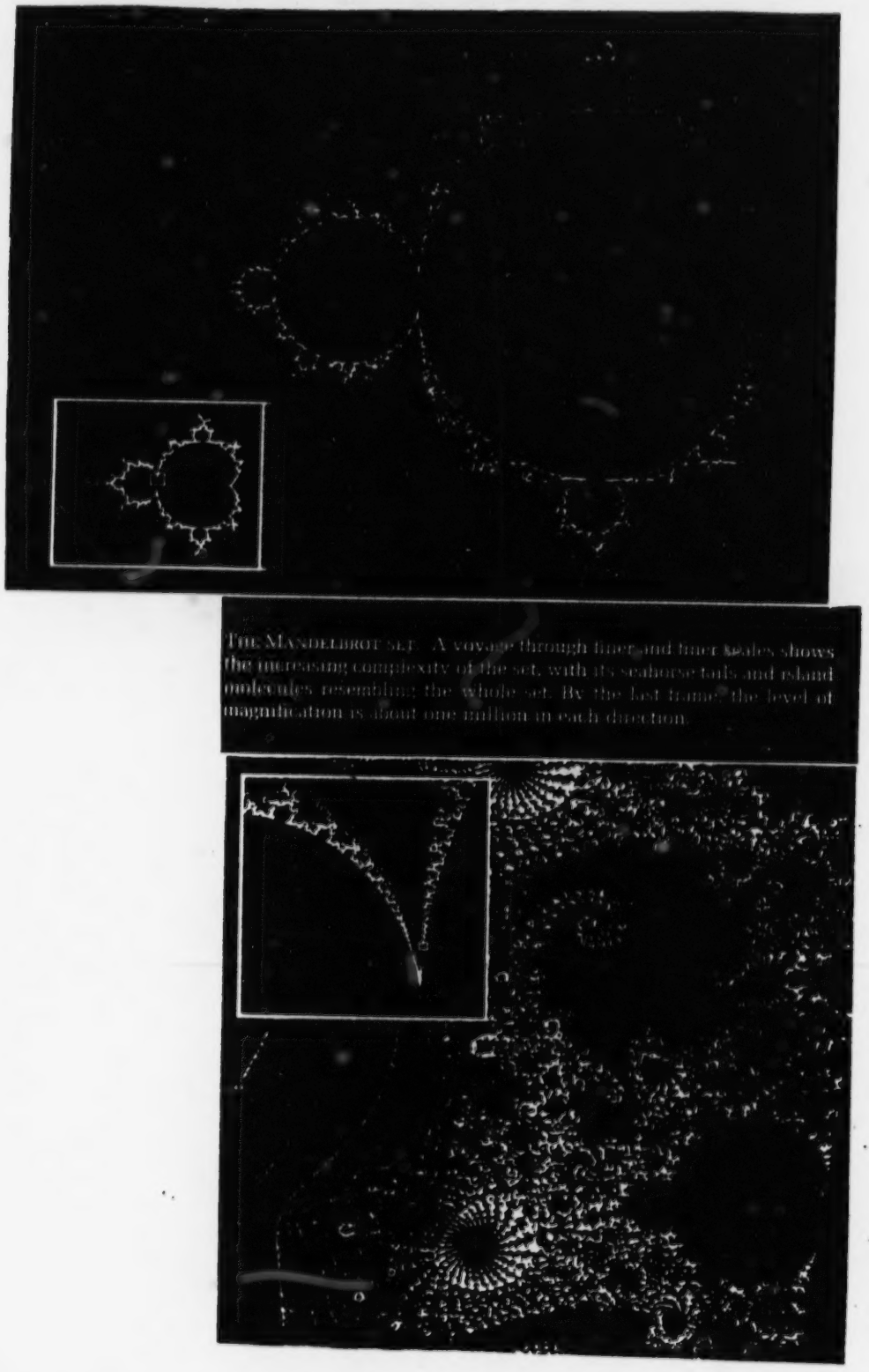


Slide 1.

(Peterson, 1988)



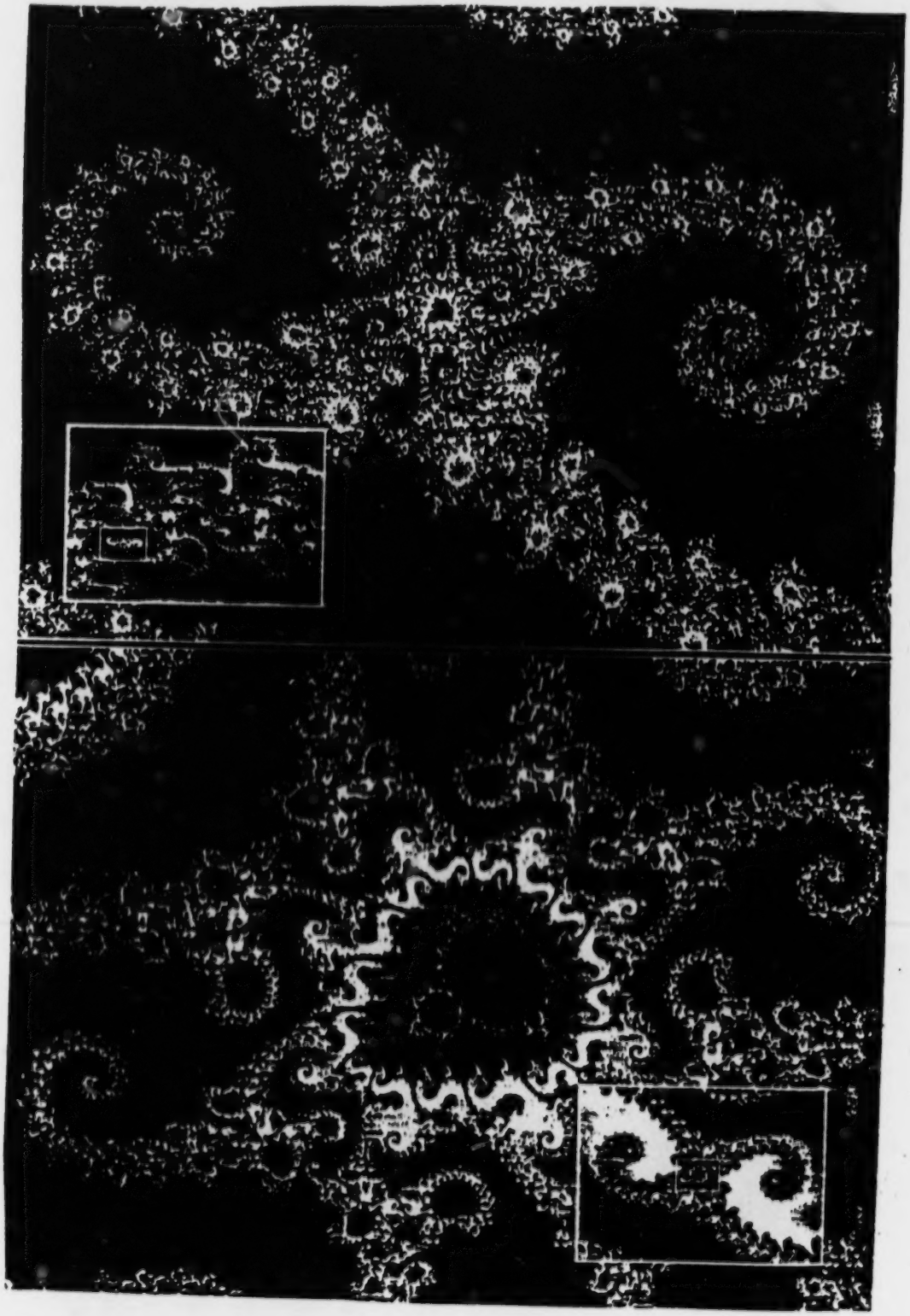
THE MANDELBROT SET. A voyage through finer and finer scales shows the increasing complexity of the set, with its seahorse tails and island molecules resembling the whole set. By the last frame, the level of magnification is about one million in each direction.

Slide 2.

(Gleick, 1987)

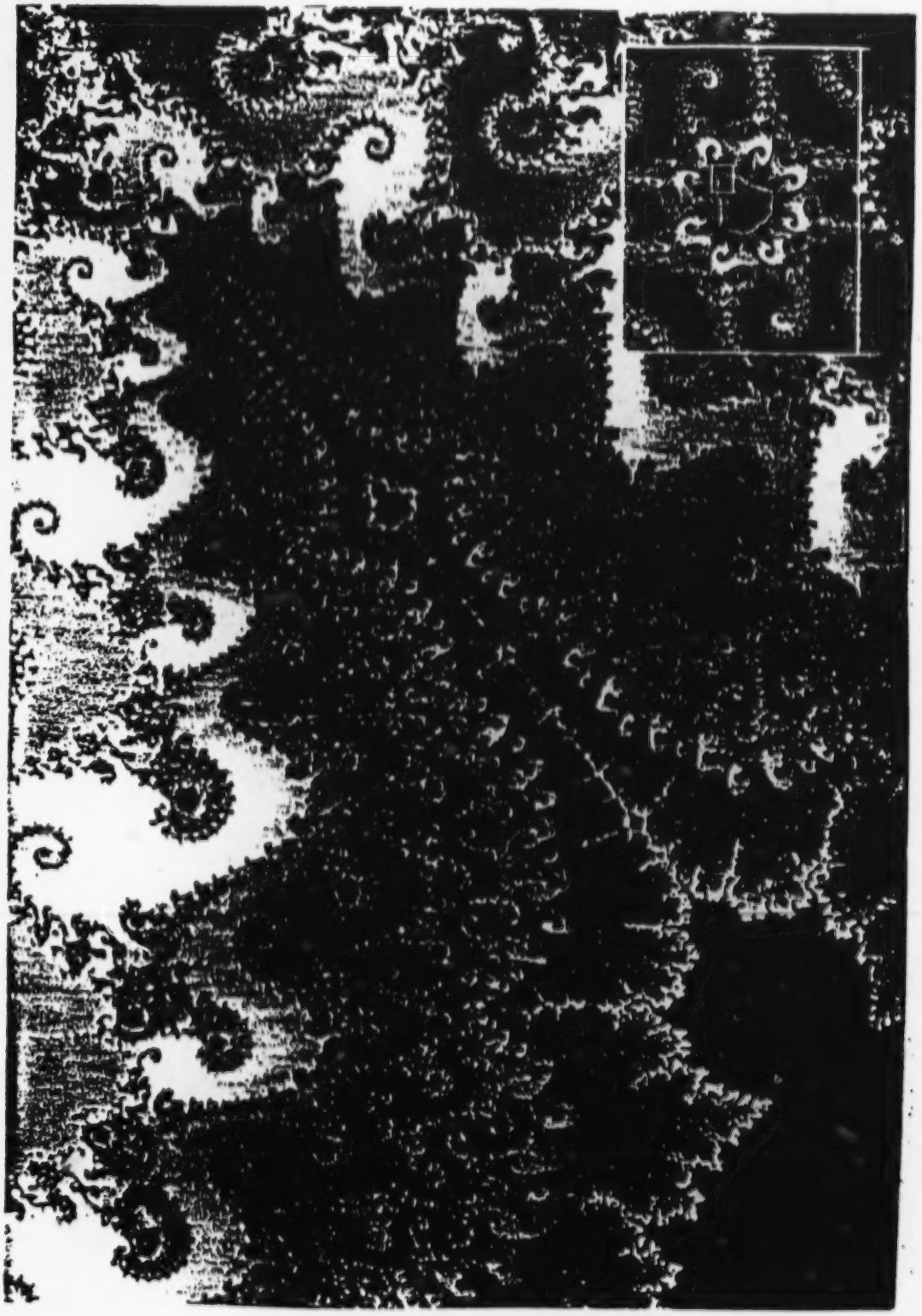
Slide 3.

(Gleick, 1987)



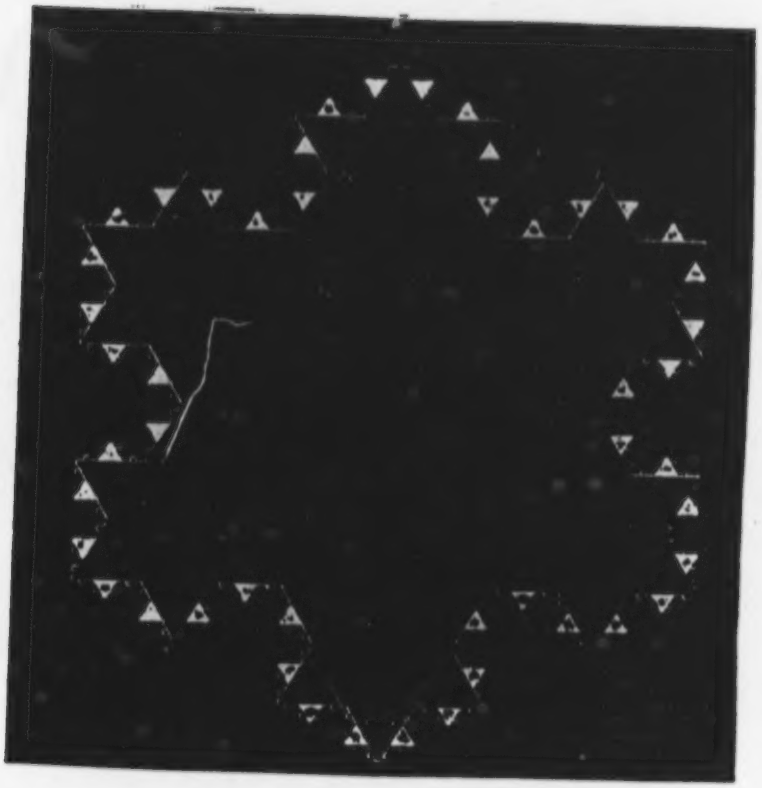
Slide 4.

(gleick, 1987)



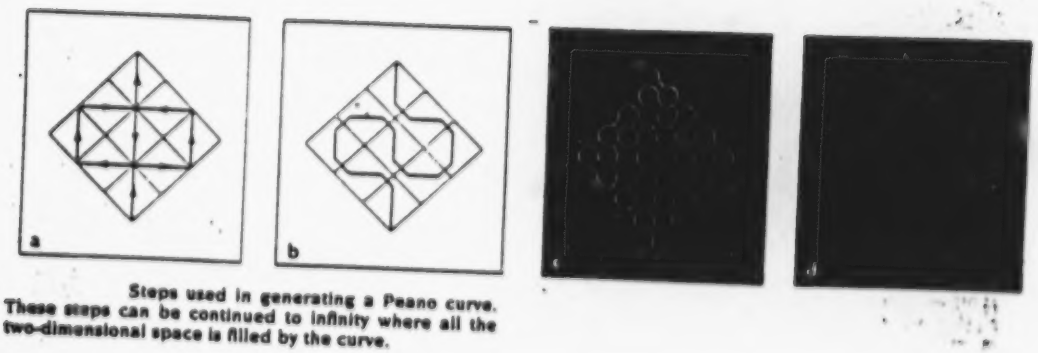
Slide 5.

(Gleick, 1987)



Slide 6.

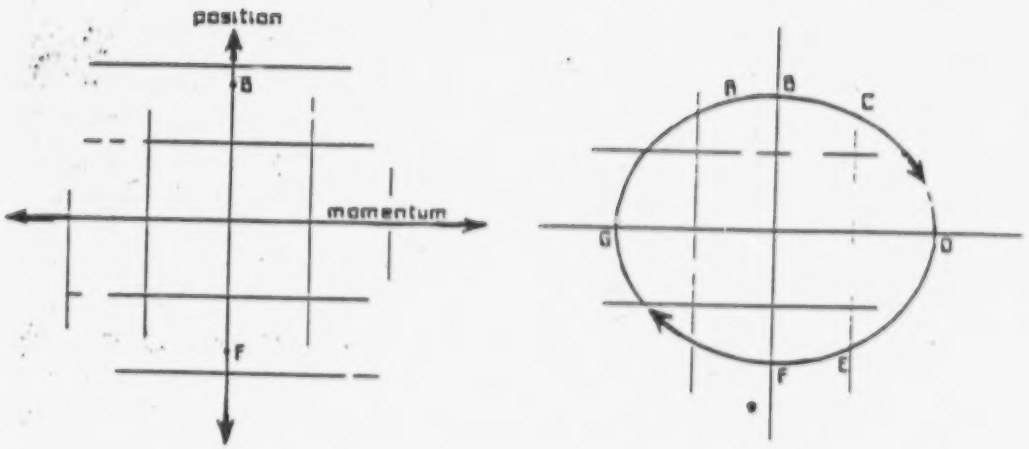
(Gleick, 1987)



Steps used in generating a Peano curve. These steps can be continued to infinity where all the two-dimensional space is filled by the curve.

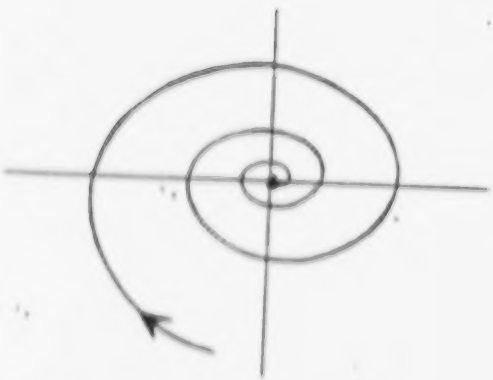
Slide 7.

(Briggs & Peat, 1989)



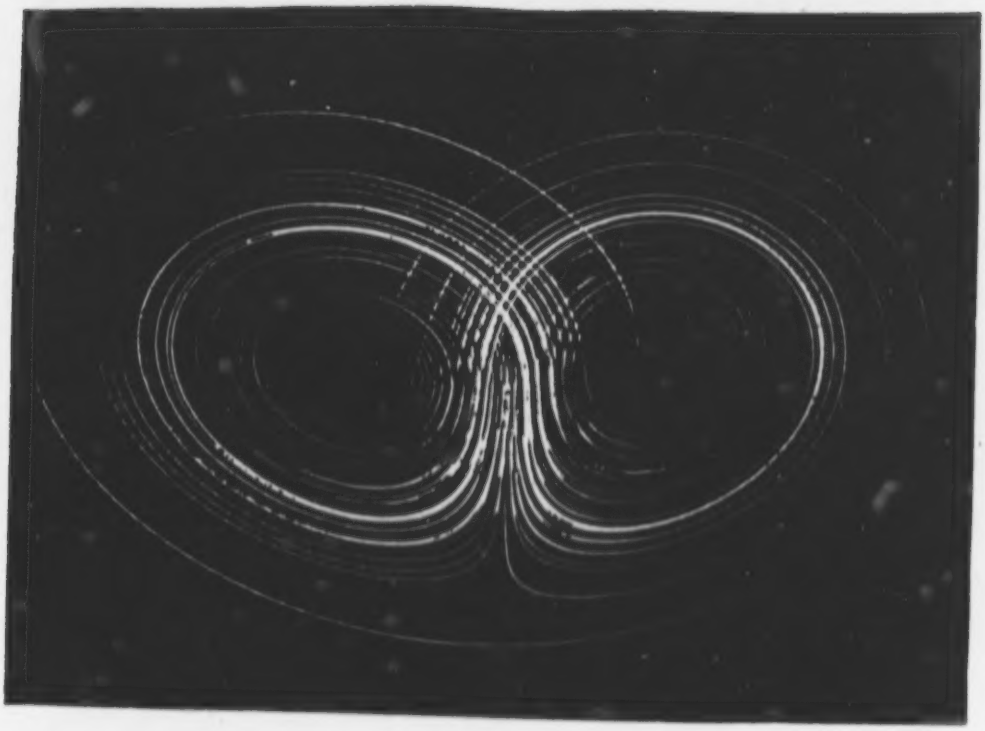
Slide 8.

(Briggs & Peat, 1989)



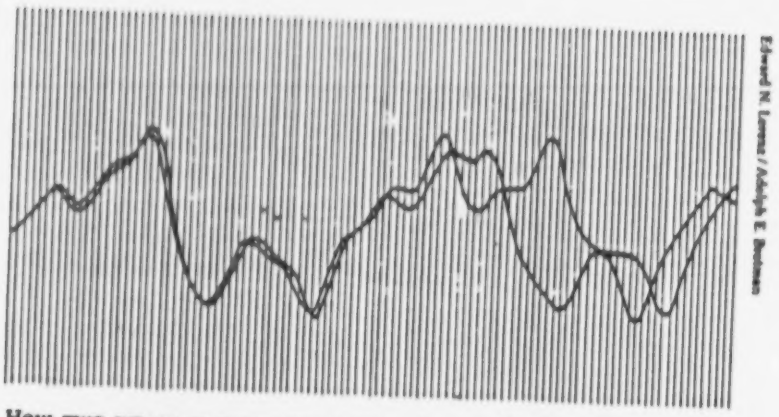
Slide 9.

(Briggs & Peat, 1989)



Slide 10.

(Gleick, 1987)



Edward N. Lorenz / Adolph E. Bentman

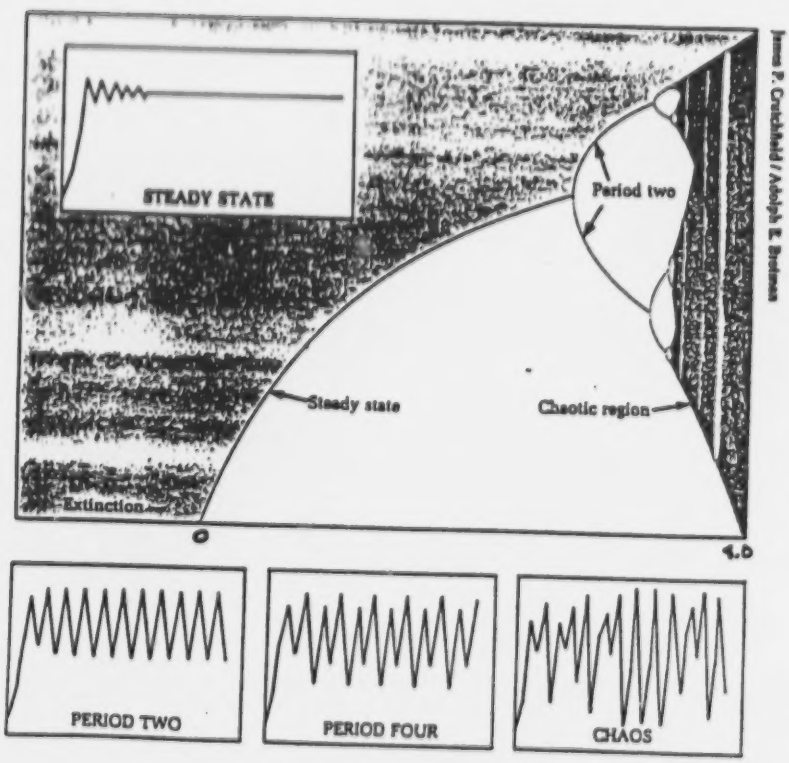
HOW TWO WEATHER PATTERNS DIVERGE. From nearly the same starting point, Edward Lorenz saw his computer weather produce patterns that grew farther and farther apart until all resemblance disappeared. (From Lorenz's 1961 printouts.)

Slide 11.

(Gleick, 1987)

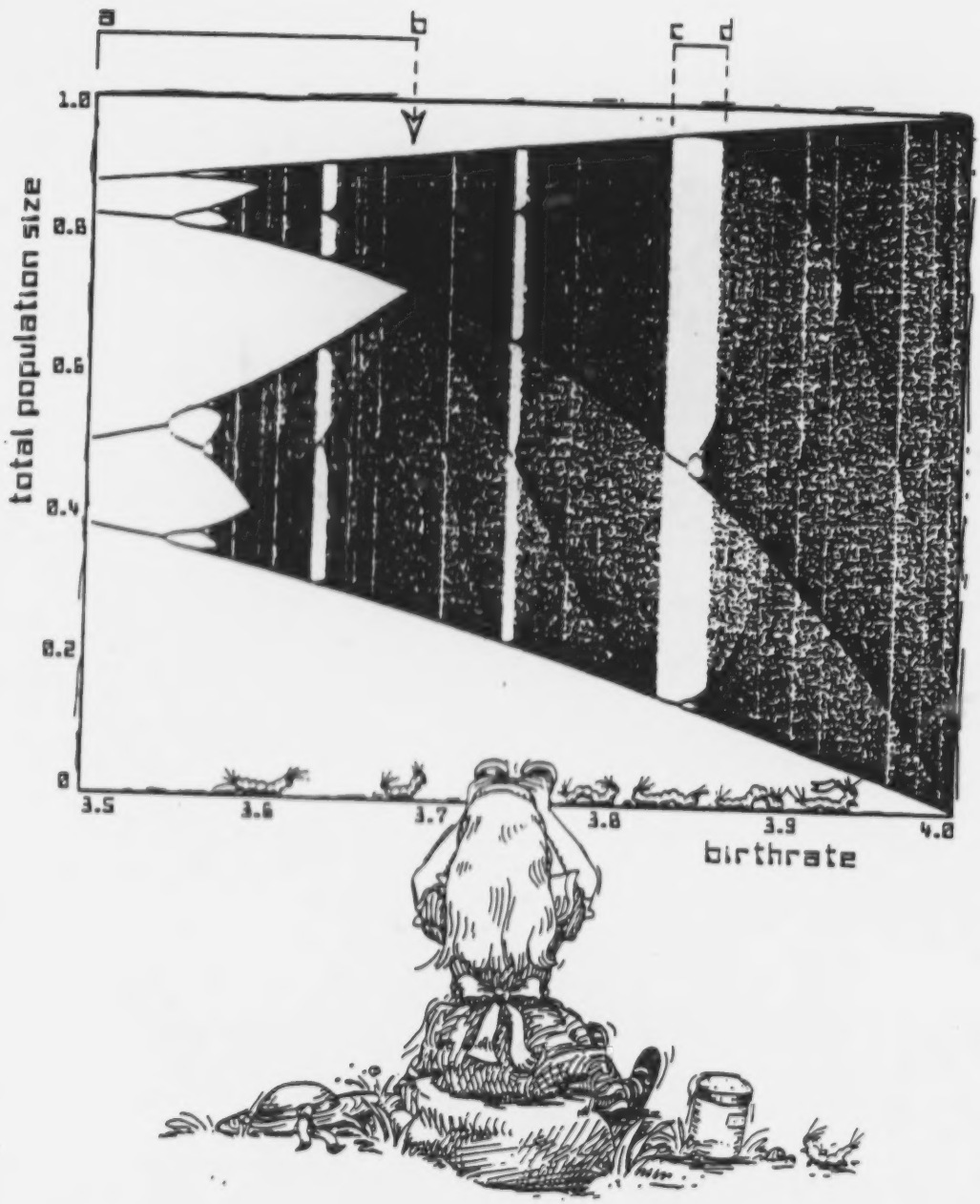
Slide 12.

(Briggs & Peat, 1989)



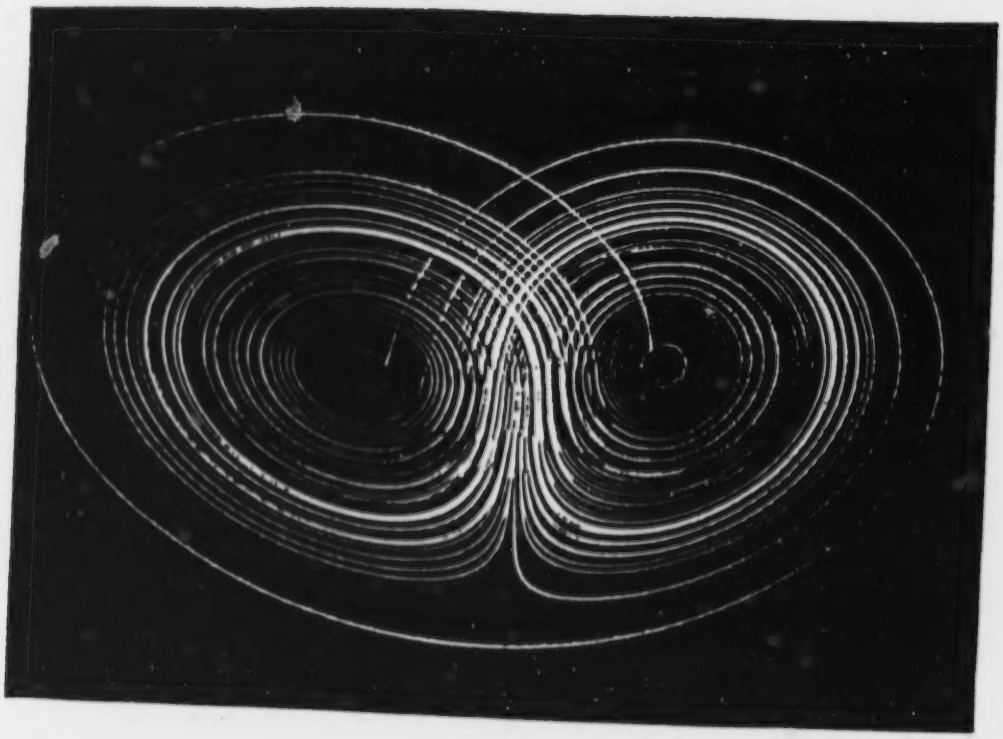
Slide 13.

(Gleick, 1987)



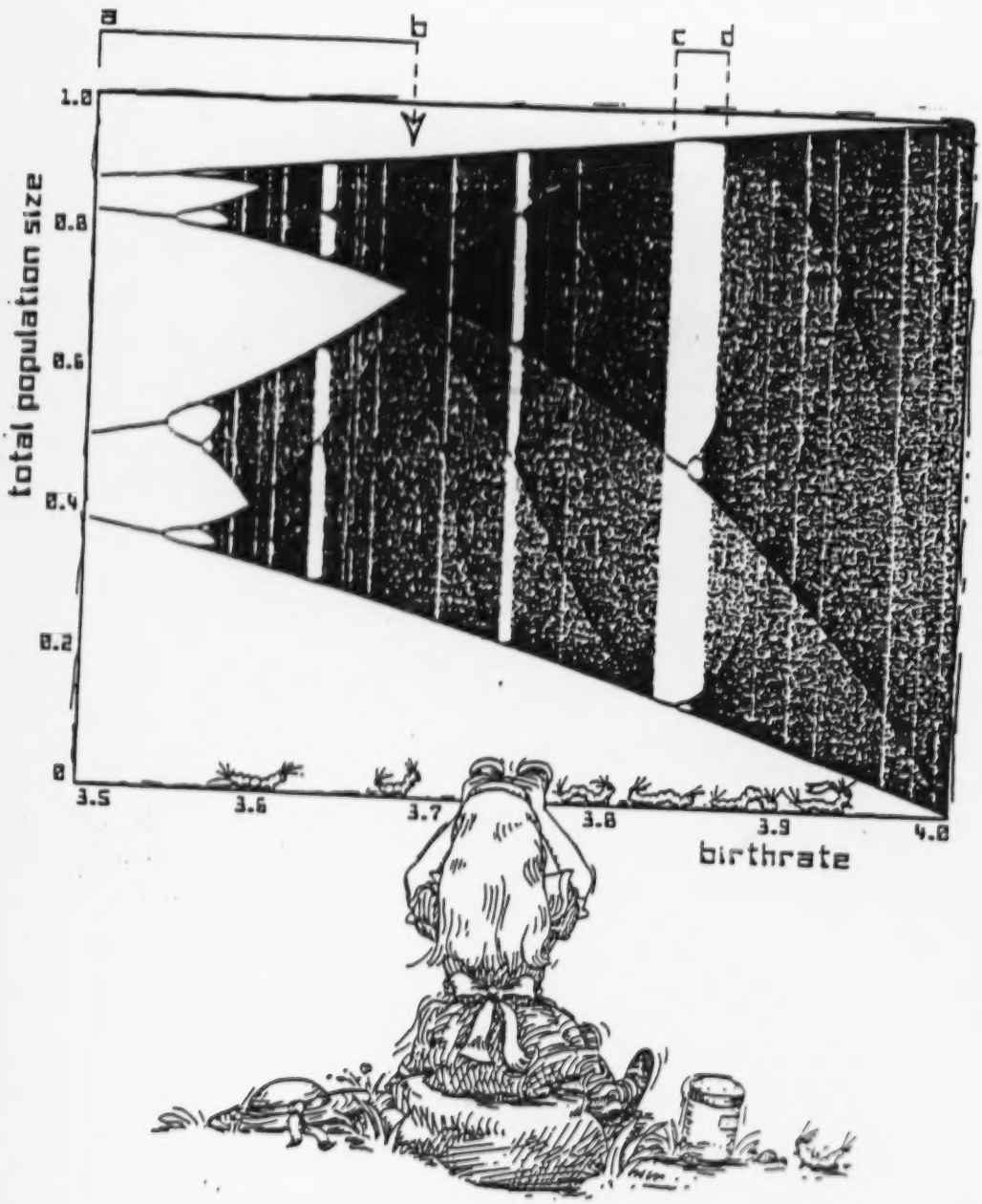
Slide 14.

(Briggs & Peat, 1989)



Slide 15.

(Gleick, 1987)



Slide 16.

(Briggs & Peat, 1989)